Modeling of Coastal Ocean Flow Fields

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LONG-TERM GOALS

To understand the dynamics of physical oceanographic circulation processes on continental shelves and slopes with emphasis on the mechanisms involved in across-shelf transport.

OBJECTIVES

To apply numerical circulation models to process studies and to simulations of continental shelf and slope flow fields, including the nearshore surf zone, to help achieve understanding of the flow dynamics.

APPROACH

Numerical finite-difference models based on the primitive equations and the shallow-water equations are applied to two- and three-dimensional flow problems relevant to the dynamics of continental shelf and slope flow fields. At present, the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987) is being utilized for studies with the primitive equations. A shallow-water equation model has been developed and applied to studies involving vorticity dynamics of currents in the nearshore surf zone. The numerical experiments are supplemented with analytical studies whenever possible.

WORK COMPLETED

Research has continued on the nature of symmetric and baroclinic instabilities in oceanic bottom boundary layers under downwelling conditions. Model studies of two-dimensional (variations across-shore and with depth, uniformity alongshore), time-dependent, wind-forced, stratified downwelling circulation on the continental shelf (Allen and Newberger, 1996) have shown that the near-bottom offshore flow can develop time- and space-dependent fluctuations involving spatially-periodic separation and reattachment of the bottom boundary layer. This results in the formation of slantwise circulation cells with horizontal scales 2-4 km and vertical scales 20-60 m. Based on the observation that the potential vorticity, initially less than zero everywhere, is positive in the region of the fluctuations, this behavior was identified as finite amplitude slantwise convection resulting from a symmetric instability. To support that identification, we have pursued a study with the objective of analytically determining the linear stability of a near-bottom oceanic flow over sloping topography with conditions dynamically similar to those in the downwelling circulation. A second objective is to establish a link between the instabilities observed in the wind-forced downwelling problem and the results of recent theoretical studies of bottom boundary layer behavior in stratified oceanic flows over sloping topography (e.g., Garrett, MacCready, and Rhines, 1993). These objectives have been addressed by investigating the two-dimensional linear stability and the nonlinear behavior of the steady, inviscid, “arrested Ekman layer” solution produced by transient downwelling in one-dimensional models of stratified flow adjustment over a sloping bottom. Further linear stability analyses and numerical experiments addressing both two and three-dimensional aspects of symmetric instabilities in bottom boundary layers have also been undertaken.

Numerical experiments addressing the nature of nonlinear, finite amplitude shear instabilities of alongshore currents in the surf zone through the solution to idealized, forced, dissipative, initial-value problems have been performed. Bottom topographies with constant slope (i.e., a plane beach), with an alongshore-uniform sand bar, and with an alongshore variable sand bar, are used with periodic boundary conditions in the alongshore direction. Forcing effects from obliquely incident breaking surface waves are calculated from gradients in the radiation stress tensor. These are determined using the formulation of Thornton and Guza (1986) generalized, for the alongshore variable topography, to two-dimensional situations. Dissipative effects are modeled by linear bottom friction.

A major new effort has involved adaptation of the Princeton Ocean Model (POM) for studies of the three-dimensional, short-wave-averaged circulation in the surf zone and adjacent inner shelf. Parameterized forcing from breaking waves, represented by gradients in the radiation stress tensor, and parameterized effects of near-surface wave-induced mass flux are incorporated. Forcing is provided by the wave transformation model of Thornton and Guza (1986) with the gradients of the radiation stress tensor partitioned as surface stresses and depth-independent body forces following Fredsoe and Deigaard (1992). The wave-induced mass flux is included through appropriate boundary conditions on the vertical velocity at the surface.

RESULTS

A linear stability analysis of the steady, inviscid, two-dimensional, “arrested Ekman layer” (Allen and Newberger, 1998) shows that this flow is unstable to symmetric instabilities and confirms that a necessary condition for instability is positive potential vorticity in the bottom layer. Numerical experiments show that for two-dimensional initial-value problems the unstable, time-dependent, nonlinear behavior in the boundary layer involves the formation of slantwise circulation cells with characteristics similar to those found in the wind-forced downwelling circulation. An extension of the linear stability analysis to allow for three-dimensional disturbances shows the existence of additional baroclinic instabilities with variations in both the across-shelf and alongshore directions. Corresponding three-dimensional numerical experiments for the “arrested Ekman layer” initial-value problem show growth of instabilities with evolution in time from quasi two-dimensional slantwise circulation cells to energetic larger horizontal scale three-dimensional baroclinic disturbances (Allen and Newberger, 1999).

In the study of nonlinear shear instabilities of alongshore currents in the surf zone over plane beaches (Allen, Newberger and Holman, 1996), the nature of the flow depends on a dimensionless parameter Q, which is the ratio of an advective to a frictional time scale. For Q above a critical value, instabilities develop. A robust characteristic of these instabilities is the rapid evolution, after initial growth at the wavelength of the most unstable linear mode, into larger-wavelength, nonlinear, propagating, unsteady wavelike disturbances. In contrast, with shore-parallel sand bar topography and with forcing from the

Thornton-Guza (1986) submodel, as Q is increased, the flow becomes increasingly unsteady exhibiting a transition from equilibrated shear waves to a turbulent shear flow (Slinn, Allen, Newberger, and Holman, 1998). The results with alongshore-uniform sand bar topography point to the possible existence in the nearshore surf zone of an energetic eddy field associated with instabilities of the alongshore current. Results from experiments with alongshore variable sand bars (Slinn, Allen, and Holman, 1999) show significant influence of alongshore topographic variability on the nearshore circulation. In particular, one notable feature is the tendency for contours of both the time mean and the root mean square vorticity fields to align along contours of constant depth.

Initial applications of POM to surf zone circulation studies have focused on alongshore-uniform two-dimensional motion with spatial variations in the across-shelf (x) and vertical (z) directions. Numerical experiments have been completed for steady flow over plane and barred beaches. We show preliminary results in Figure 1. The horizontal grid spacing is 1 m with 60 vertical sigma levels. The horizontal domain size is 600 m with depth variations 0.1 m to 12 m for the plane beach and 0.1m to 6.6 m for the barred beach. Forcing is calculated as described in Slinn et al. (1998) using the same parameters and conditions for the incident waves. The radiation stress gradients are calculated as in Slinn et al. (1999). The waves are incident at an oblique angle of 20° from the normal direction to the beach which results in forcing of an alongshore current v. The vertical z and across-shore x structure of the alongshore current v and of the streamfunction ψ for the across-shore flow for both the plane and the barred beach are shown. Of particular note here for the barred beach is the relatively large distortion in the structure of the v field due primarily to the variations in the across shore transport of alongshore momentum related to the momentum shear dispersion mechanism described by Svendsen and Putrevu (1994). Vertical profiles of the across-shelf velocity u and of v at different values of x from the plane beach experiment are also plotted in Figure 1. The resulting mean flow velocity profiles appear qualitatively reasonable compared with observations. Work is in progress conducting numerical experiments with observed bottom topography and forcing conditions to enable direct comparison of model results with the velocity measurements of Garcez Faria et al. (1998) from the DUCK'94 field experiment.

IMPACT/APPLICATIONS

Studies of the dynamics of a stratified coastal ocean model over continental shelf topography under downwelling conditions show new flow features. These include the formation and structure of downwelling fronts and the development of finite amplitude symmetric and baroclinic instabilities in the bottom layer. The occurrence of symmetric and baroclinic instabilities in the bottom boundary layer appears to be a potentially important and robust feature of transient downwelling circulation on the continental shelf. The results of the study of nonlinear shear instabilities of alongshore currents in the nearshore surf zone indicate the possible existence over plane beaches of new finite-amplitude shear waves with properties not predicted by linear theory and the possible presence over barred beaches of an energetic eddy field.

TRANSITIONS

RELATED PROJECTS

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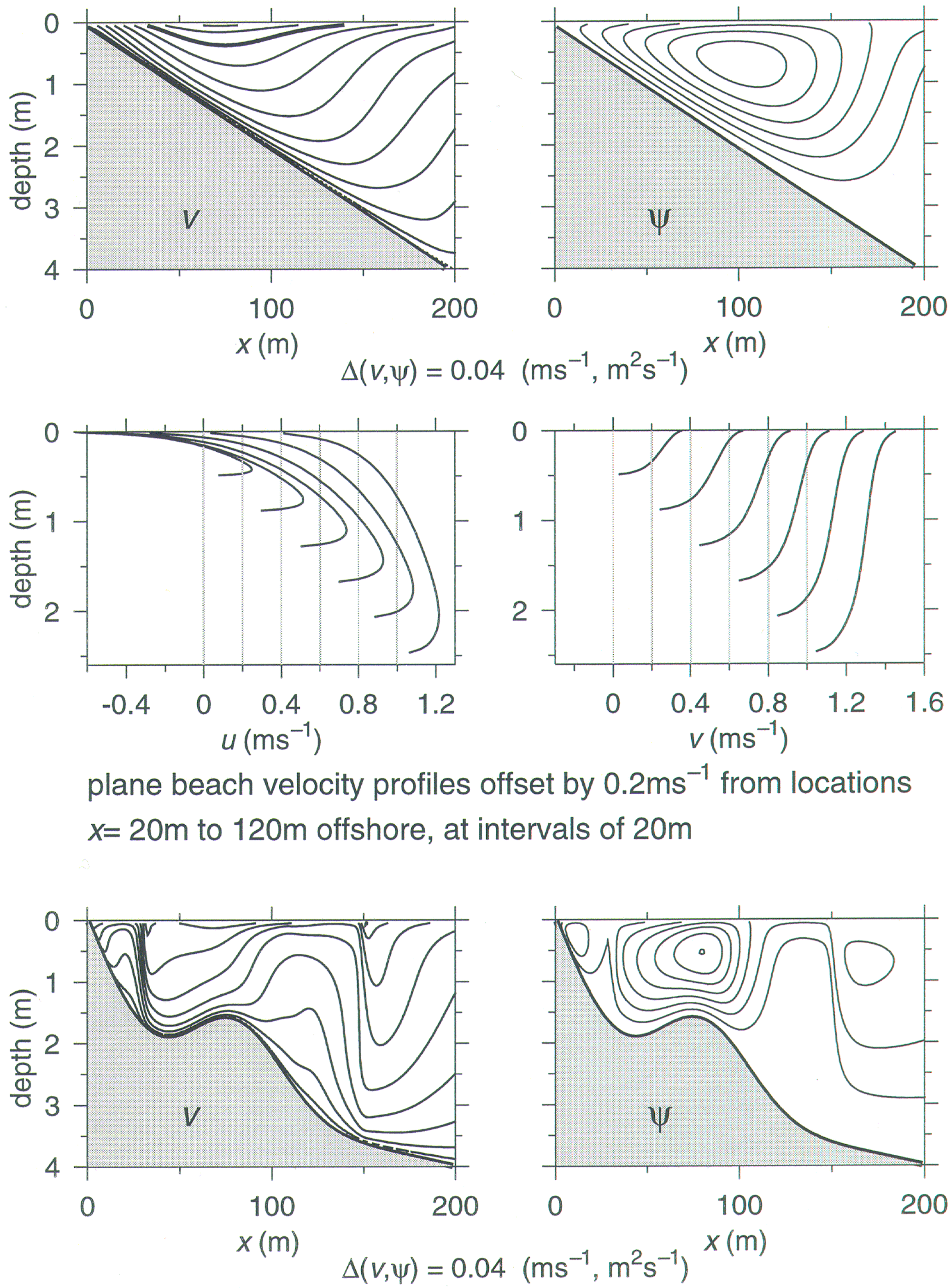

Figure 1. Preliminary results from numerical experiments using POM for steady, two-dimensional short-wave averaged flow in the surf zone forced by obliquely incident breaking waves. The (x,z) structure of the alongshore velocity v and the streamfunction ψ for the across-shore flow are shown for both a plane beach and a barred beach. Vertical profiles of the across-shore velocity u and of v are shown for the plane beach.